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# Movement and biological activity of drip-applied 1,3-dichloropropene and chloropicrin in raised mulched beds in the southeastern USA

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**Abstract: Movement and biological activity of 1,3-dichloropropene (1,3-D) and chloropicrin applied through drip irrigation in raised beds was investigated at three locations in the southeastern USA. Tests were conducted in fields with dense populations of nutsedge (*Cyperus* spp), with one location also having a high level of soil nematodes, both of which served as biological indicators of the distribution of effective concentrations of 1,3-D and chloropicrin. Objectives were (1) to gain a better understanding of 1,3-D and chloropicrin movement and the extent of biological activity outside of the wetted bed area, and (2) to examine the effect of application rate, application concentration and subsequent irrigation events on movement and activity of 1,3-D and chloropicrin. InLine®, an emulsifiable concentrate containing 60.8% w/w 1,3-D and 33.3% w/w chloropicrin, was injected into polyethylene mulched beds through the drip tubes and water movement in the beds was visualized by adding a blue dye to the injection system. Gas concentrations of 1,3-D and chloropicrin in soil were measured using Gastec® detection tubes at different positions relative to the drip tube at 1–4 days after InLine application. After one week, mulch was removed and nutsedge survival evaluated at different positions in the bed. High concentrations of 1,3-D and chloropicrin were measured at the bed center and midway between the bed center and the shoulder, but concentrations were low at the bed shoulder. Width of nutsedge control was significantly greater than width of water movement. Plant-parasitic nematodes were controlled over the entire bed width, but nutsedge re-emerged at the bed shoulders regardless of treatment. Higher application rates and concentrations of 1,3-D + chloropicrin resulted in higher fumigant concentrations in soil air. Irrigations subsequent to application reduced soil air concentrations of 1,3-D and chloropicrin and increased water movement, as did the use of two drip tubes instead of one. The data show that the pesticidal activity of 1,3-D + chloropicrin extends beyond the waterfront and indicate a significant degree of fumigant activity of emulsifiable 1,3-D + chloropicrin. However, unlike plant-parasitic nematodes, nutsedge could not be controlled over the entire bed width, regardless of rate, concentration and volume of water applied.**


**Keywords:** 1,3-D; chloropicrin; drip fumigation; polyethylene mulched beds; nutsedge; nematodes

## 1 INTRODUCTION

Micro-irrigation tubing is widely used for the delivery of water and fertilizer in polyethylene film mulched beds, especially by vegetable growers.[1] Drip irrigation systems also can be used to apply emulsified formulations of soil fumigants, a technique that has received increased interest with the pending discontinuation of methyl bromide.[2] Compared with conventional shank methods of injection, application of emulsified formulations through drip irrigation systems would be economical, more environmentally friendly, reduce worker exposure and allow for simultaneous or sequential application of a combination of fumigants. Drip fumigation differs from other soil fumigant applications in that it requires an understanding of the effects of initial soil water conditions

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and knowledge of the hydraulic characteristics of the soil to be treated.[3]

Due to improvements in crop yield, water and weed management, plasticulture in the southeastern USA will probably increase. Currently, plasticulture systems in the eastern USA are used primarily for field production of tomato, pepper, strawberry and cucurbits. Total annual revenues of the vegetable industry range from $631 million in Georgia to $1.54 billion in Florida.[4] In the subtropical climate of the southeastern USA, polyethylene film mulched beds are commonly used for two or three crops before they are destroyed. Soil-borne pests and diseases usually become a problem on the second and third crops and often can only be controlled by applying pre-plant pesticides through the drip tape. Among the most damaging pests in plastic mulch vegetable culture in the southeastern USA are the nutsedges [(*Cyperus rotundus* L (purple nutsedge) and *C esculentus* L (yellow nutsedge)] and the root-knot nematodes (*Meloidogyne incognita* (Kofoid & White) Chitwood and *M arenaria* (Neal) Chitwood).[5] Nutsedges are perennial weeds that are propagated primarily by energy-rich tubers and are characterized by rapid spread and long persistence in infested areas.[6] Yellow nutsedge is capable of producing more than 700 tubers per plant over a 32-week growing season.[7] Nutsedges are difficult to control where established, and are capable of penetrating polyethylene film, unlike most species of weeds.[7] Root-knot nematodes have a very wide host range. They typically cause problems in sandy soils, especially during summer and fall when temperatures are high.

InLine®, an emulsifiable concentrate containing 60.8% w/w (815 g liter$^{-1}$) 1,3-dichloropropene (1,3-D) plus 33.3% w/w (446 g liter$^{-1}$) chloropicrin is one of the more promising short-term alternatives to methyl bromide for application through the drip irrigation system.[3] The combination of both chemicals can be expected to provide adequate nematicidal and fungicidal activity, but control of nutsedges has been more variable.[8,9] A major problem, however, for successfully applying pre-plant soil pesticides through the drip system is that the soils used for plastic mulch vegetable production in the southeastern USA are difficult to wet completely with drip irrigation systems. These deep sandy soils, with 90% or more sand, drain rapidly and have limited lateral water movement. Recent research has focused on optimizing the distribution of drip-applied water in an effort to improve delivery of emulsified soil fumigants through these drip systems.[3,10] Although emulsified 1,3-D moves largely with the water in which it is applied, its vapor phase has been shown to diffuse beyond the area wetted by drip-applied water.[3]

The current study was conducted to gain a better understanding of the movement of emulsified 1,3-D and chloropicrin in raised, sandy beds and to evaluate its activity outside the wetted area. It was also conducted to examine the effect of application rate, application concentration, pre- and post-fumigation irrigation events and number of drip tubes on the movement and activity of 1,3-D and chloropicrin.

## 2 MATERIALS AND METHODS

Trials were initiated at the University of Georgia's Coastal Plain Experiment Station, Tifton, GA (July 15, 2002), the University of Florida's Gulf Coast Research and Education Center, Bradenton, FL (July 31, 2002) and the University of Florida's North Florida Research and Education Center, Quincy, FL (October 8, 2002). Soil types were Fuquay loamy sand (88% sand, 9% silt, 3% clay) at Tifton, EauGallie fine sand at Bradenton (97% sand, 2% silt, <1% clay), and Dothan loamy fine sand (88.5% sand, 4% silt, 7.5% clay) at Quincy. All soils had less than 2% organic matter.

Plots were located in fields with dense populations of nutsedge, which served as a biological indicator of the distribution of effective concentrations of 1,3-D and chloropicrin. Raised beds were formed using a commercial tractor-drawn bed-former. Drip tape was installed together with black polyethylene film mulch. Plastic mulch was low-density polyethylene (LDPE, thickness 50 μm). Drip tape was placed 2–4 cm below the surface in Tifton, and on the surface in Bradenton and Quincy. Beds were covered with polyethylene film mulch about two weeks prior to application at Tifton and Quincy. At Bradenton, the beds were formed about three months prior to application. Heavy summer rains and resulting flooding of the test site prohibited application at two weeks as planned. The drip tape at Quincy and Tifton was Chapin® (30.48-cm emitter spacing between emitters and a flow rate of 1.14 liter h$^{-1}$ at 0.069 MPa). At Bradenton, the drip tape was T-Tape® (30.48-cm emitter spacing, delivering 1.03 liter h$^{-1}$ at 0.069 MPa). Beds were 8.2 m long at Tifton and 6.1 m long at Bradenton and Quincy. Width of the bed tops was 76 cm at Tifton and Bradenton and 91 cm at Quincy. Bed height was *ca* 20 cm at all locations. Spacing between bed centers was 1.82 m at Tifton and Quincy and 1.51 m at Bradenton. All plots were replicated four times in a randomized complete block design.

InLine® was injected into plots through the drip irrigation system over a period varying from 3 to 7 h (Table 1). This was done with a battery-operated Even-Flo® pump which pumped pre-mixed solutions from a 60-liter tank. Flow was calibrated to deliver the 60 liters in the appropriate irrigation times. At all three sites, 327 liters per treated hectare were applied in concentrations of 1000 and 1500 mg liter$^{-1}$ of 1,3-D. In Bradenton and Quincy, rates of 243 liters and 327 liters per treated hectare were applied at a concentration of 1500 mg liter$^{-1}$ of 1,3-D. In Quincy, both rates (at a concentration of 1500 mg liter$^{-1}$) were applied using single and double drip tape configurations. In Tifton and Bradenton, the effect

**Table 1.** Treatments and application variables for InLine [1,3-D + chloropicrin] drip fumigation trials at Tifton, GA, Bradenton, FL and Quincy, FL, 2002

| Treatment/location | Rate (liter ha$^{-1}$) | Concentration (mg liter$^{-1}$) | Soil moisture[a] | Drip tubes | Subsequent irrigation?[b] | Injection Time (h min) | Irrigation water (liter m$^{-2}$) |
|---|---|---|---|---|---|---|---|
| Tifton, GA | | | | | | | |
| 1 | 327 | 1500 | Dry | 1 | No | 4.12 | 17.2 |
| 2 | 327 | 1500 | Wet | 1 | No | 4.12 | 17.2 |
| 3 | 327 | 1000 | Dry | 1 | No | 6.18 | 25.7 |
| 4 | 327 | 1000 | Wet | 1 | No | 6.18 | 25.7 |
| 5 | 327 | 1500 | Dry | 1 | Yes | 4.12 | 17.2 + 25.7 |
| 6 | 327 | 1500 | Wet | 1 | Yes | 4.12 | 17.2 + 25.7 |
| 7 | 0 | — | Dry | 1 | — | — | — |
| 8 | 0 | — | Wet | 1 | — | — | — |
| Bradenton, FL | | | | | | | |
| 1 | 243 | 1500 | Dry | 1 | No | 3.29 | 12.8 |
| 2 | 243 | 1500 | Wet | 1 | No | 3.29 | 12.8 |
| 3 | 327 | 1500 | Dry | 1 | No | 4.40 | 17.2 |
| 4 | 327 | 1500 | Wet | 1 | No | 4.40 | 17.2 |
| 5 | 327 | 1000 | Dry | 1 | No | 7.00 | 25.7 |
| 6 | 327 | 1000 | Wet | 1 | No | 7.00 | 25.7 |
| 7 | 327 | 1500 | Dry | 1 | Yes | 4.40 | 17.2 + 25.7 |
| 8 | 327 | 1500 | Wet | 1 | Yes | 4.40 | 17.2 + 25.7 |
| 9 | 0 | — | Dry | — | — | — | — |
| 10 | 0 | — | Wet | — | — | — | — |
| Quincy, FL | | | | | | | |
| 1 | 243 | 1500 | Dry | 1 | No | 3.8 | 12.8 |
| 2 | 327 | 1500 | Dry | 1 | No | 4.12 | 17.2 |
| 3 | 327 | 1000 | Dry | 1 | No | 6.18 | 25.7 |
| 4 | 243 | 1500 | Dry | 2 | No | 3.8 | 12.8 |
| 5 | 327 | 1500 | Dry | 2 | No | 4.12 | 17.2 |
| 6 | 0 | — | Dry | — | — | — | — |

[a] Tifton soil: dry = 7.8% moisture; wet = 10.3% moisture; Bradenton soil: dry = 11.4% moisture; wet = 11.9% moisture.
[b] Subsequent irrigation was applied for 3.5 h at one and two days after application.

of pre-fumigation soil moisture ('wet' and 'dry' plots) and of subsequent irrigation was also investigated. To achieve 'wet' and 'dry' plots at Tifton, the wet plots were irrigated through the drip system from noon to 8:30 h in the evening the day prior to application. Soil moisture immediately prior to application was determined as 7.8 and 10.3% in the dry and wet plots, respectively. At Bradenton, high soil moisture precluded similar pre-application irrigation. The field used was historically wetter at one end, so the field was divided into wet and dry ends, and plots assigned accordingly. Soil moisture determined by the gravimetric method[11] immediately prior to application was 11.4 and 11.9% in the dry and wet plots, respectively. The effect of post-fumigation water (subsequent irrigation) was investigated by operating the drip system for 3.5 h at 1 and 2 days after an initial application of 327 liters of fumigant at 1500 mg liter$^{-1}$. Blue marking dye (Signal™, Precision Laboratories Inc) was injected into all plots concurrent with the chemical injection (1 liter dye/400 liter of water delivered to the plots) so that the extent of water movement could be determined.[12] Following each treatment, the drip system in each plot was allowed to run for an additional 15–30 min, depending on length of irrigation lines, to purge remaining chemical from drip tubes. Treatments and application parameters are given in Table 1.

Gas concentrations of 1,3-D and chloropicrin in soil were measured using the Gastec® detection tubes 132HA (scale range = 50–500 mg liter$^{-1}$) and 132L (scale range = 2–25 mg liter$^{-1}$). These tubes measure trichloroethylene and do not differentiate between 1,3-D and chloropicrin. Therefore, the measured concentrations will be referred to as 'fumigants' and are total concentrations for both 1,3-D and chloropicrin (InLine). Readings from Gastec tubes are not quantitative and are therefore not presented in mg liter$^{-1}$ but rather as relative concentrations (percentage of initial concentration at 0 cm depth) and will be referred to as relative fumigant concentrations (RFCs). The actual measurement range of these tubes depends on the amount of air that is drawn, and ranges from 20 to 1300 mg liter$^{-1}$ (132HA) and from 1 to 70 mg liter$^{-1}$ (132L). Lower limits of detection (LOD) are 4 mg liter$^{-1}$ for the 132HA tubes and 0.4 mg liter$^{-1}$ for the 132L tubes. Fumigant concentrations were measured on 4 consecutive days following application. Each day measurements (four replicates) were taken in the bed center (0 cm from drip tape), midway between

the bed center and bed shoulder [19 cm (Tifton and Bradenton) and 22.5 cm (Quincy) from drip tape], and at the bed shoulder [38 cm (Tifton and Bradenton) and 45 cm (Quincy) from drip tape]. Measurements were taken from a 1.25-cm diameter, 15-cm-deep hole cored into the bed at each location. A Sensidyne® Gas Detection Pump (Model AP-1S) was used to draw 50–200 ml of air, depending on sensitivity of the tube and levels present in the soil, from each hole through the detection tube. A soil temperature probe was inserted into one bed at each site just before injections were done and retrieved after terminating the tests. Reported temperatures are averages for this period.

At Quincy, Gastec readings were taken at two locations in relation to the drip emitters to determine the effect of proximity to drip emitters on Gastec readings. One set of samples was drawn at a location level with the drip emitters, a similar set of samples at locations halfway between two emitters.

At 7–8 days after application, plastic mulch was removed from one-half of each plot and the location of drip tube emitters were marked with surveyor's flags. Width of nutsedge control was measured in a 5-cm band centered on an emitter and in a similar band located between emitters. A trench was then excavated across the bed at the level of the emitter and at a level midway between emitters and the width of the dye pattern was measured. In Tifton, nutsedge tuber viability was also evaluated in the greenhouse by following the emergence pattern of nutsedge tubers for 30 days. Nutsedge tubers were collected 2 days after removing the plastic from the bed center, midway between the bed center and bed shoulder, and at the bed shoulder. Four soil cores (golf cup cutter cores) were collected from each location. After washing the soil from the tubers, tubers from each plot and for each location were counted, planted into designated pots and the germination patterns were followed for 28 days, counting the number of shoots at 7, 14, 21 and 28 days after planting. At 28 days, pots were screened again and the number of tubers counted.

In addition to nutsedge control, biological activity of InLine in Tifton was also assessed by its effect on soil nematodes. Nematode soil populations were determined before fumigation from 10 soil cores (2.5 cm diameter × 25 cm deep) from each plot. After removing the mulch, separate samples (five cores each) were taken from the bed center, midway between the bed center and bed shoulder, and at the bed shoulder. Soil cores were mixed, and nematodes were extracted from a 100-$cm^3$ sub-sample with a modified Baermann method.[13]

All data were analyzed using ANOVA or GLM procedures (SAS software, version 8) with mean separation according to LSD. Nematode data were transformed to log $(x + 1)$ wherever necessary according to a normality test.

## 3 RESULTS

### 3.1 Spatial and temporal distribution of InLine concentrations in soil air

Soil air concentrations of InLine decreased with increasing distance from the injection point. At 1 day after fumigation, relative fumigant concentrations in soil air (RFCs) in different bed locations ranked as follows: center (150–300 RFC) > midway (50–150 RFC) > shoulder (5–25 RFC) (Fig 1). High InLine concentrations showed faster decrease with time, and by day 2 concentrations in the center were down to values of 50–80 RFC, and differences between bed positions became smaller. By day 4, levels of InLine at all bed positions were below 50 RFC.

InLine levels immediately following fumigation were lower at Quincy than at Bradenton and Tifton, where, except for higher concentrations in Tifton at 2 days, InLine levels were similar. However, at 3 and 4 days after fumigation, InLine levels, except for the shoulder, were higher in Quincy than in Bradenton and Tifton.

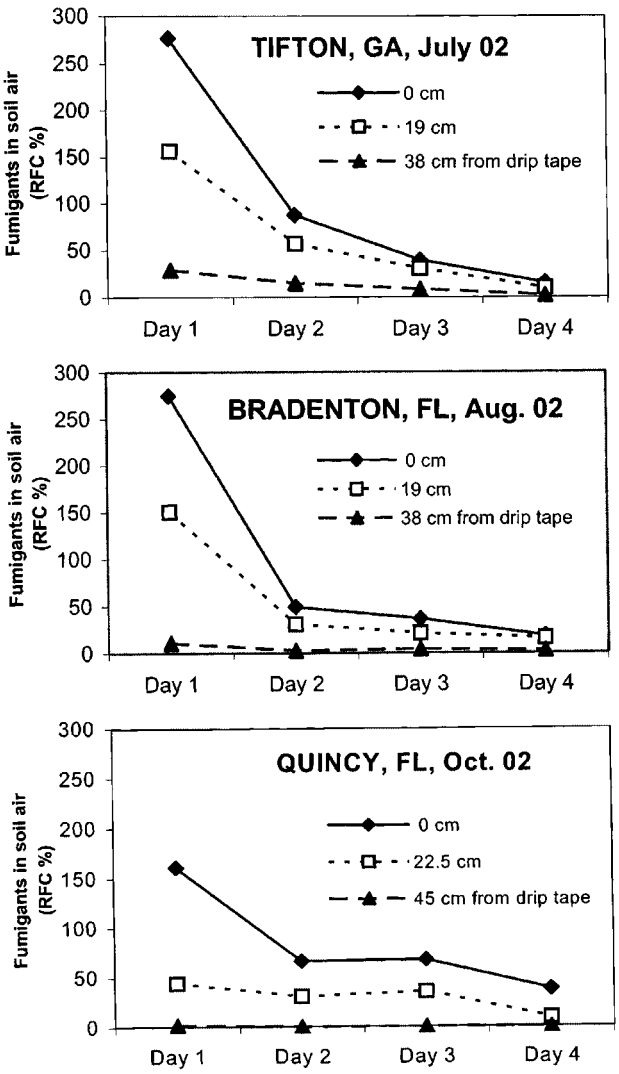


**Figure 1.** Time-concentration curves for soil air concentrations of 1,3-D + chloropicrin at different positions in the bed in Tifton, GA, Bradenton, FL and Quincy, FL, July–October 2002. Concentrations are relative fumigant concentrations (RFCs) expressed as percentage of initial concentration at 0 cm depth.

At the bed shoulders, InLine levels were low at all sites and over the 4 days varied from 2 to 29 RFC in Tifton, from 2 to 11 RFC in Bradenton and from 0 to 2 RFC in Quincy.

Gas readings taken on drip emitters as compared to between emitters (Quincy only) were similar when taken in the center (24.4 RFC on emitters versus 23.7 RFC between emitters) or shoulder (2.4 RFC both on and between emitters) of the bed. A significant difference ($P < 0.05$) was observed when gas readings were taken midway between the bed center and shoulder (24.8 RFC on emitters versus 18.4 RFC between emitters).

### 3.2 Water movement (dye patterns) and biological activity of InLine

The blue dye produced circular fronts on the bed surface that, at the higher irrigation regimes, eventually coalesced and formed blue bands perpendicular to the drip line between the emitters.[12] After removal of the mulch and drip tape, beds were sliced vertically and distinct dye patterns were found on the soil face. These patterns were generally wider when measured on emitters as opposed to between emitters. When averaged across all trials, the width of the dye pattern from a single drip tube averaged 36.1 cm on emitters and 30.9 cm between emitters. This translated into 40–55% bed coverage in Tifton and Bradenton (76-cm-wide beds) and 22–39% in Quincy (91-cm-wide beds).

The width of the nutsedge control pattern was significantly greater than the width of the dye pattern in every treatment in every trial, and was similar when measured on emitters (65.3 cm) or between emitters (67.8 cm). The width of nutsedge control was about twice the width of water movement in these trials and covered 90–96% of the bed in Tifton and Bradenton (76-cm-wide beds) and 68–85% in Quincy (91-cm-wide beds) (Fig 2). In Quincy, dye pattern widths with two drip tubes were 66.5 and 61.2 cm (75 and 69% bed coverage) when measured on and between emitters, respectively (Fig 3G). However, the width of nutsedge control at Quincy was still significantly greater than the width of the dye pattern, averaging, respectively, 83.6 and 81 cm (94 and 92% bed coverage).

Viability of nutsedge tubers in the greenhouse in Tifton varied from 30 to 50% for the non-treated beds (Fig 4). Nutsedge germination in the bed centers of drip-fumigated plots was completely suppressed up to 28 days after planting (DAP), whereas the area in between the center and the shoulder of the bed showed between 0 and 6% nutsedge germination. At the bed shoulders nutsedge germination was similar for all treatments at 20–30% (Fig 4). Nutsedge germination reached its peak at 14 DAP and few tubers were found germinating after that time. In general, nutsedge could not be controlled at the bed shoulder (Fig 5).

Plant-parasitic nematodes in Tifton were root-knot nematode (*Meloidogyne incognita*), ring nematode (*Mesocriconema* spp), sting nematode (*Belonolaimus longicaudatus* Rau) and stubby root nematode (*Paratrichodorus* spp). Initial nematode populations (before treatment application) were 128 root-knot, 132 ring, 34 stubby root and 16 sting nematodes per 150 $cm^3$ soil. After removal of plastic mulch 8 days after fumigation, 57 plant-parasitic nematodes (29 root-knot, 18 ring, 2 stubby root and 8 sting nematodes) were recovered from untreated beds, compared with less than 1 from fumigated beds. Free-living nematodes were bacteriovores (Rhabditidae), fungiovores (Aphelenchoideae and *Tylenchus* spp) and omniovores (free-living Dorylaimidae). Total initial free-living nematode population (before treatment application) was 178 nematodes per 150 $cm^3$ soil (75% bacteriovores, 20% omniovores and 5% fungiovores). After removal of plastic mulch, 185 free-living nematodes were recovered from untreated beds, compared with less than 7 from fumigated beds. Only bacteriovores were recovered following fumigation; on average 1 nematode per 150 $cm^3$ soil in the centers and mid-sections of the bed, and 16 nematodes per 150 $cm^3$ soil at the bed shoulders.

### 3.3 Effect of application rate

Average soil air concentrations of InLine were consistently twofold higher in plots treated with 327 liter $ha^{-1}$ than in plots treated with 243 liter $ha^{-1}$ (Figs 2A and B). This was regardless of site (Bradenton or Quincy) and bed location. Only in Quincy at the bed shoulders of the one-tape treatment were InLine levels too low (<1 RFC for both rates) to measure a difference.

The higher application rate required more water to apply (17.2 liter $m^{-2}$ versus 12.8 liter $m^{-2}$) (Table 1), and resulted in wider dye patterns, especially when measured between drip emitters (Figs 3A and B). Nutsedge control in the field was consistently improved in plots treated with 327 liter $ha^{-1}$ over plots treated with 243 liter $ha^{-1}$. Differences in nutsedge control were small and not significant on the 76-cm-wide beds in Bradenton (~1% improvement) (Fig 3A). On the 91-cm-wide beds in Quincy, greater differences were observed, ranging from 7% when measured on drip emitters to 15% when measured between emitters (Fig 3B).

### 3.4 Effect of application concentration × time factor

Application concentrations of 1500 mg $liter^{-1}$ resulted in significantly higher (45–78%) InLine soil air levels in all three tests compared with concentrations of 1000 mg $liter^{-1}$ (Figs 2C and D). Significant differences among trial sites ($P = 0.03$) were noted for the bed shoulders, and greatest differences between high and low application concentrations were recorded in Tifton (16 RFC and 7 RFC respectively) and Bradenton (15 RFC and 10 RFC respectively) (data not given, Fig 2C gives data averaged for Tifton and Bradenton). In Quincy, on 91-cm beds, InLine concentrations at

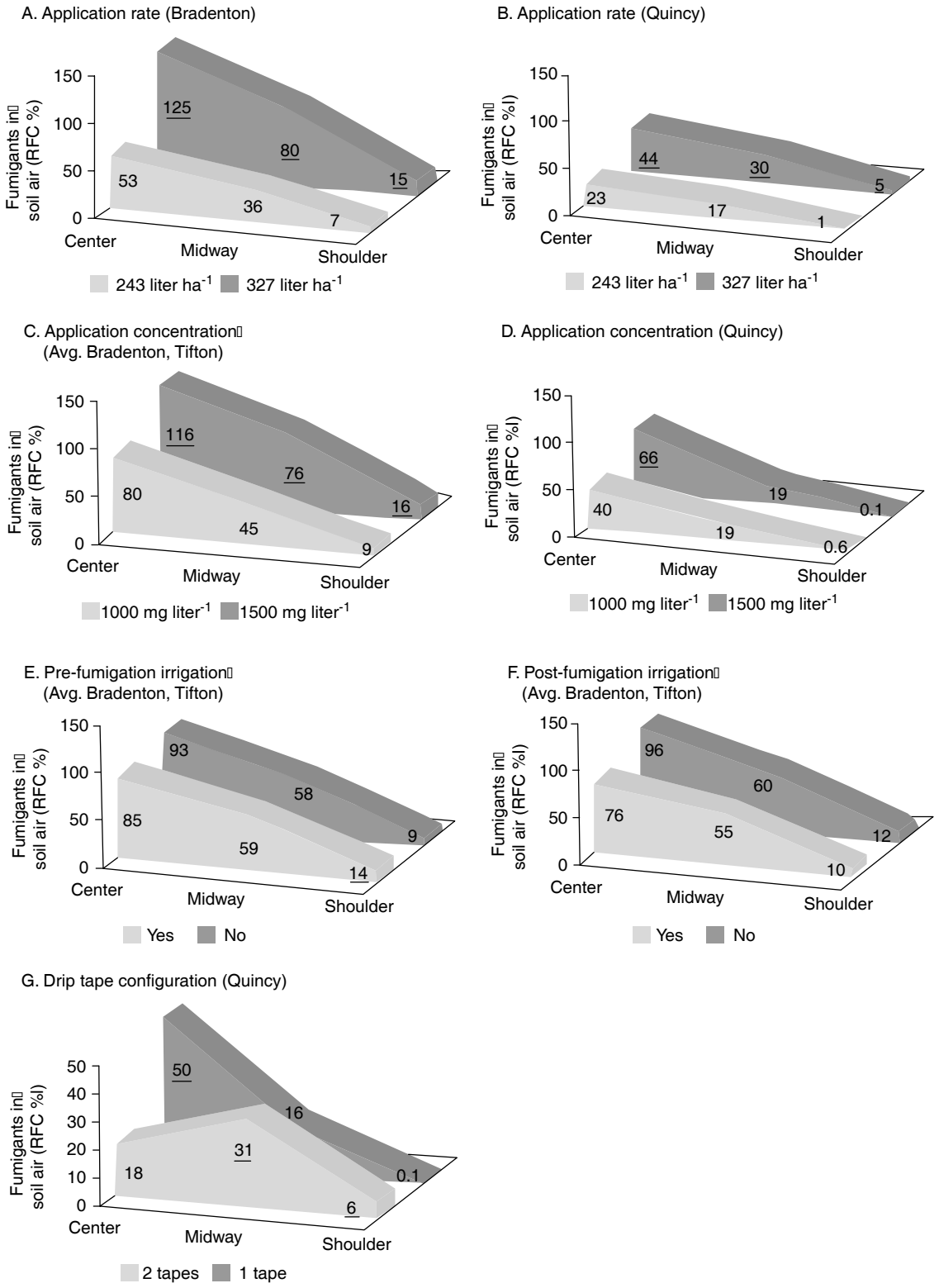


**Figure 2.** Effect of application rate and concentration × time factor, pre- and post-fumigation irrigation and number of drip tapes on relative soil air concentrations of 1,3-D + chloropicrin at different positions in polyethylene mulched beds in Bradenton, Fl, Quincy, FL and Tifton, GA. Concentrations are relative fumigant concentrations (RFCs) expressed as percentage of initial concentration at 0 cm depth. Bed width was 76 cm in Bradenton and Tifton, and 91 cm in Quincy. Bold and underlined values are significantly greater ($P < 0.05$) than corresponding values for similar bed positions.

the shoulders were <1 RFC regardless of application concentration.

Lower application concentrations required more water to apply (Table 1), and generally resulted in wider dye patterns (Fig 3C and D). However, differences in dye width were small (5% in Tifton, and 10% in Bradenton and Quincy) and not statistically different. Width of nutsedge control was greater in plots treated with the higher application concentration in Tifton (6% greater on and between emitters, data

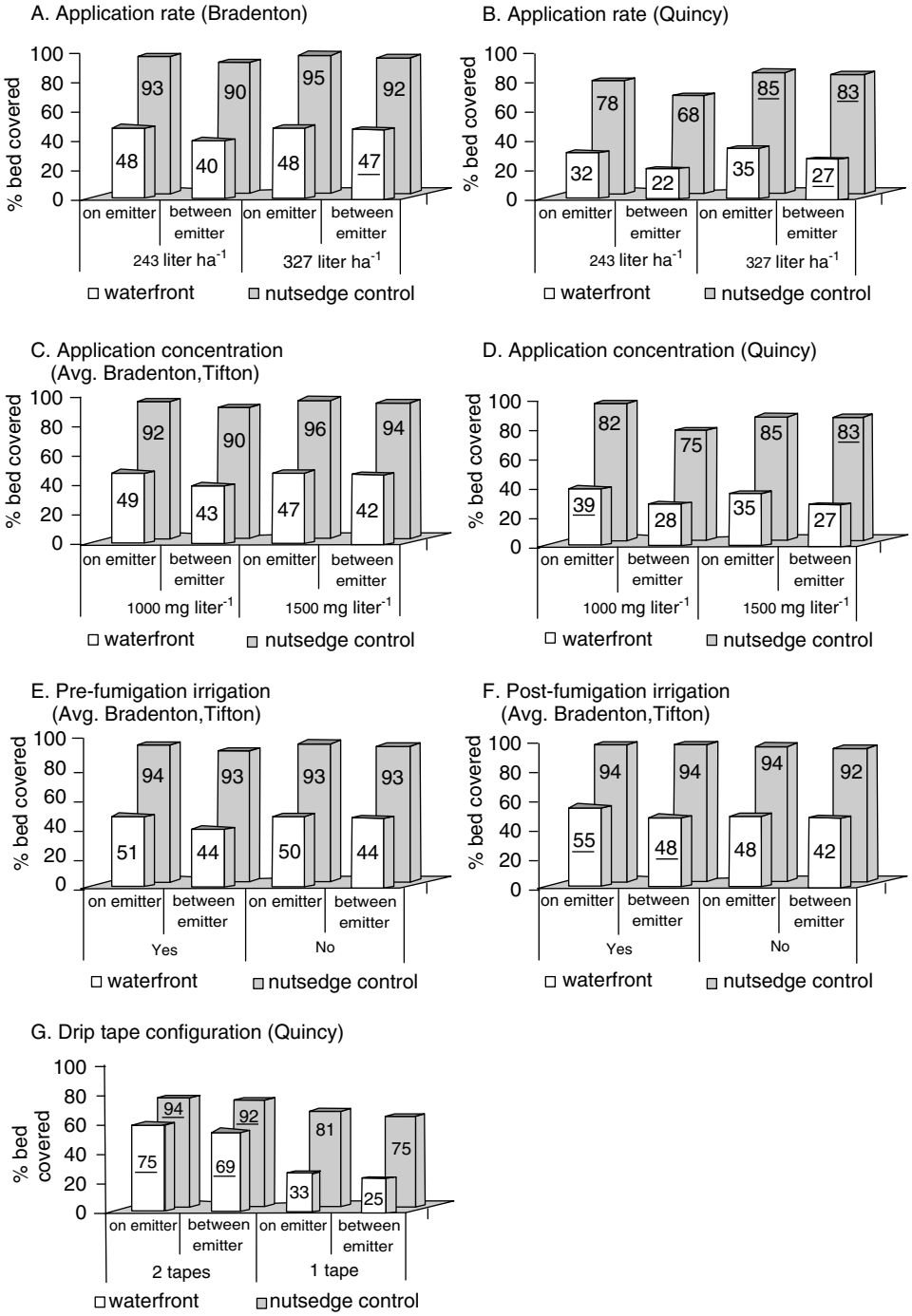


**Figure 3.** Effect of 1,3-D + chloropicrin application rate and concentration × time factor, pre- and post-fumigation irrigation and number of drip tapes on width of water movement and control of *Cyperus* spp at different positions in polyethylene mulched beds in Bradenton, Fl, Quincy, FL and Tifton, GA. Bed width was 76 cm in Bradenton and Tifton, and 91 cm in Quincy. Bold and underlined values are significantly greater ($P < 0.05$) than corresponding values for similar bed positions.

not shown), and to a smaller extent in Quincy (between emitters, Fig 3D). No improvement was observed in Bradenton. Nutsedge tuber emergence (a measure of viability) in the greenhouse in Tifton was completely suppressed for both application concentrations in the bed center. However, some nutsedge did sprout from the bed area between center and shoulder at the lower application concentration (Fig 4). At the bed shoulders, nutsedge emergence was slightly reduced at 7 DAP for the higher application concentration ($P = 0.12$), but by 14 DAP all treatments showed similarly high germination. Nematode suppression was similar with both application concentrations (see Section 3.2.).

### 3.5 Effect of pre-fumigation water applications

Despite efforts to obtain a large moisture differential between dry and wet plots, pre-fumigation differences in soil moisture were only 2.5% at Tifton and 0.5% at Bradenton. Neither moisture level resulted in consistently higher InLine soil air concentrations, but, in general, dry plots showed higher InLine soil

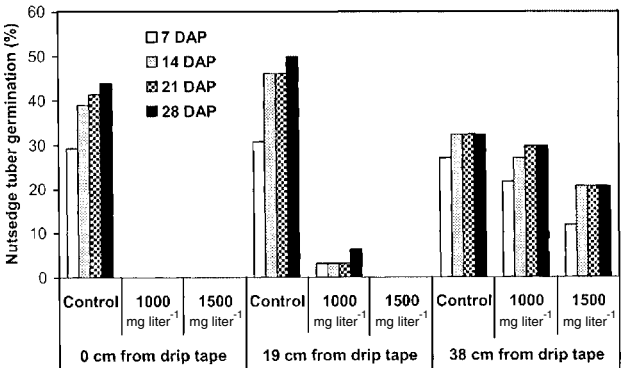


**Figure 4.** Effect of 1,3-D + chloropicrin application concentration and bed location on tuber germination patterns of *Cyperus rotundus* at 7, 14, 21 and 28 days after planting (DAP) at Tifton, GA, July 2002.

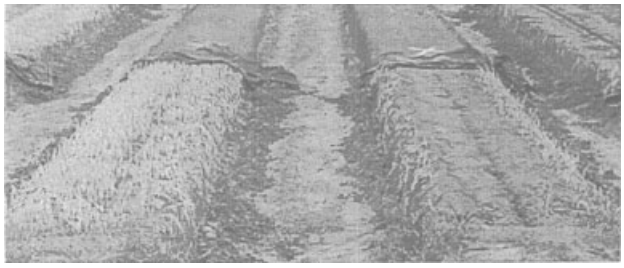

**Figure 5.** Purple nutsedge (*Cyperus rotundus*) cover after removal of black plastic mulch, (left) without and (right) with 1,3-D + chloropicrin drip-fumigation (7 days after application) at Tifton, GA, July 2002.

air concentrations at the bed centers, whereas wet plots showed higher InLine soil air concentrations at the bed shoulders (Fig 2E). Significant differences were found mostly on the more sandy Bradenton soil. In Bradenton, regardless of treatment, InLine concentrations on the bed shoulders in wet plots (18.3 RFC) were significantly higher than those in dry plots (5.6 RFC). In Tifton both dry and wet beds had similar concentrations at the bed shoulders, respectively 10 and 12 RFC. In the bed centers, InLine levels in dry and wet plots were 91 and 80 RFC in Bradenton, and 96 and 90 RFC in Tifton (data not shown).

Differences in dye patterns and nutsedge control did not show a consistent trend and were in the order of a few percent in most treatments (Fig 3E). All plant-parasitic nematodes were equally controlled regardless of irrigation, but less bacterial feeding nematodes were found in dry than in wet plots, respectively three and nine nematodes per 100 $cm^3$ soil.

### 3.6 Effect of post-fumigation water applications

Irrigating at 1 and 2 days after fumigation (Bradenton and Tifton) reduced InLine concentrations in both trials and at all three bed locations (Fig 2F). InLine concentrations in irrigated plots were, on average, 25% less in the bed center and 10–15% less midway and at the bed shoulder than non-irrigated plots. Differences, however, were not significant at either site.

Width of the dye pattern was wider with additional irrigation, except when measured between emitters at Bradenton (Fig 3F). Irrigating 1 and 2 days after drip fumigation increased water movement across the bed from 48 to 55% ($P < 0.01$) on emitters and from 42 to 48% ($P = 0.01$) between emitters. Additional irrigation did not affect nutsedge control in Bradenton, and resulted in a slight improvement in Tifton (4%, data not given; Fig 3F gives data averaged for Tifton and Bradenton). Nematode control was similar with and without subsequent irrigation (data not shown).

### 3.7 Effect of number of drip tubes

At the bed center InLine concentrations were higher with single-tube applications, but at the bed shoulder and midway between the center and shoulder they were higher with the double-tape treatment (Fig 2G). Data were averaged for both application rates (243 and 327 liter $ha^{-1}$), as both rates showed similar differences. InLine levels at the bed center and midway between center and shoulder were about twice as high with the higher application rate, regardless of the number of drip tapes. At the bed shoulder, InLine levels were less than 0.1 RFC with single-tube applications (both rates) and, respectively, 2 RFC (low rate) and 11 RFC (high rate) with double-tape applications.

The dye pattern width was significantly increased, on average two- to threefold, by the use of two tubes in all cases, although gaps in dye patterns between tubes were not taken into account (Fig 3G). Similarly, the use of two tubes improved the width of the nutsedge control pattern by, on average, 13% when measured on emitters and 17% when measured between emitters. There was more scope for improvement with the lower application rate than with the higher application rate (respectively 18 and 12% wider nutsedge control with the double-tape treatment). Despite the fact that nutsedge was controlled over a wider area with two tubes, there were some living nutsedge plants in the bed centers.

## 4 DISCUSSION

Ideally, fumigants will penetrate quickly through the soil, remain in place at an effective concentration for the required contact time and afterwards volatilize or degrade as quickly and completely as possible. Emulsified fumigants will move mainly with water, although our tests did show that gas diffusion is also important, indicating that emulsified 1,3-D + chloropicrin is volatile. In accordance with previous reports,[10,14] InLine soil gas levels were high immediately following application and close to the injection point, and decreased rapidly with time and distance from the drip emitters. The greater bed width in Quincy (20% wider than in Tifton and Bradenton) resulted in a more diluted chemical solution and lower InLine soil gas levels, which were beyond the sensitivity (LOD) of the Gastec tubes, at the bed shoulders. Also, temperature at the time of application may have affected InLine gas levels. The test in Quincy was done later in the year and average soil

temperature (26 °C) was somewhat less than in Tifton and Bradenton (29 °C). Therefore diffusion of the chemical and movement to the bed shoulder may have been reduced.[14] Lower temperatures also slow down biodegradation of 1,3-D,[15] and may explain why InLine levels at 4 days after fumigation were higher in Quincy than in Tifton and Bradenton.

Gas readings from locations on and between emitters showed only minor differences. The data suggest that reducing the number of readings and standardizing the location of these readings would reduce variability, at least when taken midway between the bed center and shoulder, where InLine concentrations showed greatest difference among emitter locations.

In general, the width of nutsedge control was about double the width of the wetted area, indicating that biological activity of 1,3-D + chloropicrin extended beyond the waterfront. This was regardless of application variables and confirms previous reports that InLine readily diffuses beyond the wetted area.[3] However, nutsedge was not controlled on the bed shoulders, regardless of application variable, confirming previous results from California.[16] Nutsedge required higher doses of InLine than root-knot and other plant-parasitic nematodes, which were controlled over the entire bed width in Tifton. Good nematode control with 1,3-D has been consistently demonstrated over the years[8,17] and the chemical is generally considered to be a better nematicide than herbicide. Chloropicrin is generally considered a weak nematicide, but may also have contributed to nematode control. InLine soil gas concentrations at the bed shoulders in Tifton averaged 15–30 RFC, which was too low to affect nutsedge tubers, but was high enough to kill plant-parasitic nematodes. The recovery of a few bacterial feeding nematodes in the bed shoulders is of little significance, as these nematodes are not a threat to crops. Their greater resistance to InLine could be due to their short life cycles and ability to rapidly colonize empty niches.[18]

The consistently good nutsedge control in our tests could be related to stimulatory or additive effects between 1,3-D and chloropicrin.[19,20] However, good control was more likely to be due to the high application rates and the fact that tests were conducted in summer when soil and air temperatures were high and nutsedge was actively sprouting. Dormant nutsedge tubers are very difficult to control. The same is true for spores of many diseases and nematode eggs. Although lack of nutsedge control on the bed shoulders could become a problem to the crop later in the season, good control at the bed center, in order to prevent nutsedge from growing through the planting holes, is more important. The relatively low germination percentage of nutsedge tubers from non-treated beds in the greenhouse (30–50%) was likely to be due to the fact that tubers are relatively short-lived (compared with seeds). It is estimated that purple nutsedge tubers have a 16-month half-life.[21]

### 4.1 Application rate and concentration

The effect of application rates and concentrations depended on site, location in the bed and volume of water applied. Increasing the application rate from 243 to 327 liter $ha^{-1}$ (Bradenton and Quincy) doubled concentrations of InLine over the entire bed width at both sites. Moreover, to maintain the same application concentration, the higher rates required 25% more irrigation water to apply, and resulted in wider wetting fronts. However, the width of the waterfront never extended out to the bed shoulders, and, as InLine levels at the bed shoulders remained low, nutsedge control in Bradenton was not improved. The wider beds in Quincy offered more scope for improvement, and higher rates improved nutsedge control at this site, especially with the double-tape configuration. Nutsedge control was especially improved in the area between drip emitters, corresponding with the relatively wider waterfronts in this area.

Higher chemical application concentration (Tifton, Bradenton and Quincy) increased InLine soil gas levels throughout the entire 76-cm-wide beds at Tifton and Bradenton, but only at the center of the 91-cm-wide beds at Quincy. The beds at Quincy proved to be too wide for effective fumigation with one drip tape. The increase of InLine soil gas levels at the center of the bed in Quincy is of little practical importance, as both application rates were equally effective at the bed center with regard to their biological activity (nematicidal as well as herbicidal). The slight increase in nutsedge control with increasing application concentration, in spite of narrower waterfronts, again confirms the substantial contribution of diffusion to the biological activity of 1,3-D emulsions.

### 4.2 Irrigation regimes

Attempts to widen the wetted bed area and push the chemical further away from the injection point using irrigation were only slightly effective. The extent to which a raised bed can be wetted depends on the soil type, the volume of water applied and the proximity to a drip emitter. The soils in our tests are typical for the southeastern USA and had a sand content of 90% or more. Such soils are highly permeable and have limited lateral water movement. Where there is no restrictive layer underlying the field, soils drain rapidly (Tifton). Where there is a restrictive layer, in-field moisture spreads out and moves into all plots, resulting in relatively uniform moisture levels (Bradenton). In general, the sandy nature of the soils in Florida and the Coastal Plains of the southeastern USA limits the extent to which a 70+-cm-wide bed can be uniformly wetted. Thus, pre-fumigation soil moisture differentials proved difficult to maintain and evaluate in these trials. Slightly higher InLine gas levels at the bed shoulders of pre-wet beds were at the expense of lower levels at the bed centers, but overall differences were small. Although soil moisture differences were smaller in Bradenton than in Tifton,

effects on InLine levels were greater, possibly because the plots in Bradenton had a history of being wet, which was not the case in Tifton.

Greater volumes of irrigation water did accomplish the desired goal of increasing lateral movement of the waterfront, but they often reduced fumigant activity (InLine concentrations in soil air). Probably the excess moisture, as a result of greater irrigation volumes, acts as a vapor barrier and prevents proper movement of the fumigant. This is the main reason why fumigation in wet soils often fails. However, similar tests done in California (with two drip tapes) reported higher 1,3-D gas concentrations with increasing amounts of irrigation water.[3] Contradictory results between California and the southeastern USA are possibly due to differences in soil, with soils in our tests being more permeable and thus more prone to chemical leaching when irrigation volumes are increased. Experimental soils in California were less sandy (~65% sand), had better water-holding capacity and more lateral capillary movement than most soils in the southeastern USA. Therefore, leaching may not have been an issue, and greater irrigation volumes may have reduced volatilization losses through the plastic by forming a water seal.[14]

Moreover, degradation of 1,3-D depends on soil type. Degradation increased with increasing soil moisture in a loamy sand soil (such as in our tests), but not in a sandy loam soil (such as in California tests).[22]

Pre- and post-fumigation irrigations had little effect on nutsedge control and, when differences were noted, control was better in beds that received less water, as they recorded higher InLine gas levels. Differences in control of nutsedge and soil nematodes were typically noted on the bed shoulders and were usually $<10\%$, probably due to the fact that, even in 'wet' plots, control was relatively good ($>80\%$). Despite the lack of differences in these trials, additional work and greater irrigation amounts may be warranted in situations where soil moisture differentials can be maintained. In our tests irrigation amounts were maximum 26 liter $m^{-2}$, which is far less than what was applied in the above-mentioned tests in California (up to 61 liter $m^{-2}$).[3]

### 4.3 Number of drip tapes

A double-drip-tape configuration was more effective in improving water movement than any of the higher irrigation volumes. It also resulted in greater InLine concentrations away from the drip tube and gave a more uniform distribution of the chemical throughout the bed. As a result, nutsedge control was substantially improved. However, survival of some nutsedge between drip tubes suggests that concentrations in the bed center were not consistently efficacious throughout the length of the bed. When crops are planted in the bed centers, the use of two drip tapes could result in lower than optimum soil fumigation in the area of the bed receiving the plants. This should be evaluated further and the impact on control of diseases and nematodes should be evaluated as well as control of nutsedge. However, one should keep in mind that growers will only adopt two-drip-tape configurations if the benefits, such as improved pest control and/or lower application rates, sufficiently outweigh the extra cost.

## 5 CONCLUSIONS

Fumigant concentrations were high at the bed center and low at the bed shoulder. This was reflected in good nutsedge control at the center of the bed, but lack of control at the shoulder, regardless of application rate, concentration or irrigation regime. The pesticidal activity of 1,3-D + chloropicrin extended beyond the waterfront and indicates that emulsified 1,3-D + chloropicrin has a significant degree of fumigant activity. Higher application rates and higher concentrations of 1,3-D + chloropicrin resulted in higher fumigant concentrations in soil air. Although greater volumes of irrigation water did accomplish the desired goal of increasing lateral movement of the waterfront, they often reduced fumigant activity. In general, the potential of irrigation management to control the movement, degradation and volatilization of fumigants in soil is questionable in the sandy soils of the southeastern USA. The double-drip-tape configuration was more effective in improving water movement and gave a more uniform fumigation pattern throughout the entire bed.

Other opportunities to improve distribution and activity of drip fumigants, including smaller bed width and increasing the water-holding capacity and lateral water movement of the beds by the use of soil amendments will be investigated in the near future.

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